

# **Design for a Unitary Graphite Composite Instrument Boom**

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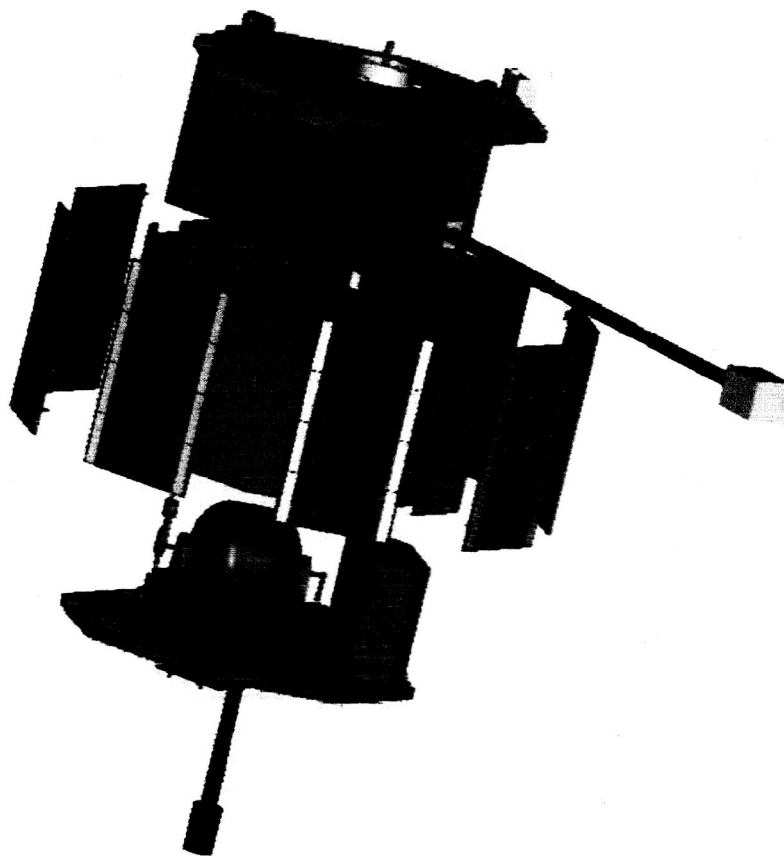
## **Abstract**

This paper describes development of a unitary graphite composite instrument boom that incorporates carpenter-tape like hinges for stowage. While light and stiff, graphite composite is not ordinarily thought of as a flexible material. This design has taken advantage of the stiffness of the composite in tubular geometry, yet leveraged its thin-section behavior to place flexibility at the required locations. Key is the proprietary layup, which results in a tough yet flexible hinge capable of rotating over 90 degrees in each direction. When the boom deploys, there is enough torque to overcome parasitic resistance from harness, etc. It will snap to the fully extended, rigid shape. The design has addressed materials issues such as out-of-plane bending, edge cracking, and inter-laminar ply separation.

## **Introduction**

This boom and hinge development effort was originally started for the Space Technology 5 (ST5) project in NASA's New Millennium Program (NMP). An overall view of the spacecraft is shown in Figure 1. Graphite composite in this application was extremely attractive for scientific, structural, thermal and electrical reasons.

- The magnetometer sensor head was sensitive down to 0.1 Nano Tesla (nT). Any metals in its proximity would have had to be non-magnetic (of these there are many structural candidates). They also would have had to be protected against thermo-magnetic effects due to internal temperature gradients. Graphite significantly reduces these concerns. The absence of metal in the entire boom support structure meant extremely low contamination of the science data collected.
- The high specific stiffness of graphite makes it ideal for this alignment-critical application.
- Graphite's low Coefficient of Thermal Expansion (CTE) keeps thermal distortion low, helping maintain alignment. Its low conduction minimizes heat loss from the spacecraft at the boom base. The black color aids in overall temperature moderation due to environmental temperature extremes.
- Lastly, graphite's electrical resistance of ~100 Ohm per square provides sufficient conduction path to bleed off accumulated charge.



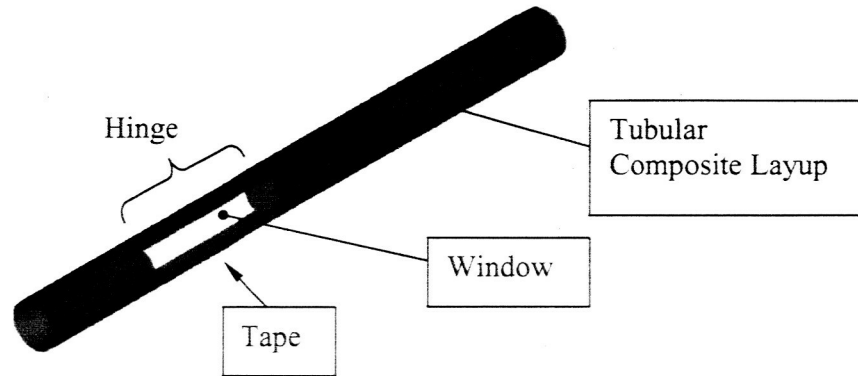
**Figure 1 Space Technology 5 Spacecraft with Unitary Composite Instrument Boom  
-Exploded View**

This unitary boom structure offers simplicity of design, manufacture and operation. Weight reduction of one order of magnitude over similar metallic boom designs is yielded in large part by the efficiency inherent in its design. The conductive properties of the graphite composite with its thermal and structural properties make it an optimum material for space use. The unitary hinge was to be part of a three-segment magnetometer boom. Due to the natural frequency constraints of this particular mission, the unitary design was abandoned in favor of a built-up version using metallic hinge elements.

#### **Description**

The boom consists primarily of a thin-wall tube of multi-layered composite construction. The hinges are formed by machining a window on each side of the tube at the desired location as shown in figure 2. The remaining material forms the hinge working element, or tape. When bent, the hinge tapes flatten and may contact each other, depending on bend angle and hinge geometry.

Bonded end fittings serve to anchor the boom base to its support structure at one end, and secure the sensor head adapter at the other. If required, thermal and electrical treatments may be applied. Harnessing to the instrument usually is run on the exterior to avoid chafing at the hinges, due to the tape contact when stowed.



**Figure 2 Unitary Boom Hinge Element Formed with Machined Windows**

### **Operation**

The hinge bends up to 90° reliably. The strain energy in the bent hinge restores the tube to its original circular shape upon release. In certain cases, the excess momentum of the release imparts compression buckling of the opposite tape and causes the hinge to “snap-over” past the straight, fully deployed position. Strain energy stored in the opposite direction returns the boom to its straight configuration. Dissipative forces in the material, harness and mounting serve to damp oscillations as well.

Stowing requires manual pressure on the inside tape to initiate the bend. The hinge could be forced to bend by applying a moment across it, inducing the same buckling condition as snap-over, but this is not recommended to preserve bend cycles.

### **Analysis**

The chief hurdle in analyzing the hinge sections was developing a non-linear, iterative approach using MSC NASTRAN® to simulate the buckling behavior.

A non-linear solution set involved geometrically large displacements and post-buckled behavior. Setting up out of plane contact between the two tapes on opposite sides of the hinge was also modeled with a “slide-line” contact definition of nodes, however it required pre-knowledge of which nodes would contact. Master and slave nodes that could interfere with each other were defined and monitored for approach and contact. A priori knowledge of which nodes those are was required, making the iterative technique laborious. Recent software revision allows this to be modeled without a priori knowledge, according to the FEM software vendor. Analyzing contact between the tapes demanded CPU times of up to 20 hours. Analyzing in-plane friction between the tapes would have been an extra burden so it was not done. This was acceptable since this friction was not significant parameter in the ultimate solution.

Normal modes analysis showed that the hinges dominate the overall boom stiffness with four-bar link behavior. Optimum window size for both stowability and maintaining boom stiffness turned out to be when ~50% of the tube material remains for the hinge tapes.

Torque versus bend angle testing came in very close to what was predicted by the non-linear analysis. Photo elastic strain coating with composite tapes showed very close qualitative correlation in strain states. The strain "hot spots" were in the same place, but the coating added to the thickness and itself contributed to the stiffness. Strain magnitudes were different by a factor of ~5. This is consistent with the thicker and therefore stiffer test item compared to the actual tape.

Overall, the analysis effort was successful. It accurately modeled post-buckled behavior deformed shapes and is shown in Figures 3 and 4, even showing the slight asymmetry of the post-buckled hinge.

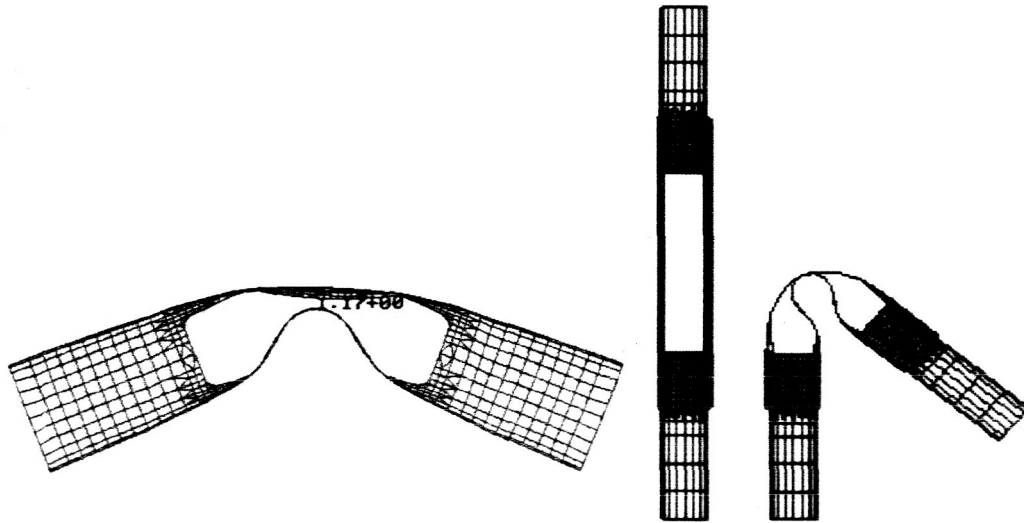


Figure 3 FEM of Post-Buckled Unitary Composite Hinge



Figure 4 FEM of Boom with Unitary Composite Hinge Second Mode Shape



### Requirements and Design

Scientific and space craft level requirements for the boom were as follows:

- Deployed Frequency shall be  $8 \text{ Hz} \pm 3 \text{ Hz}$
- Instrument position shall be repeatable within  $0.25^\circ$
- Magnetic signature at sensor head shall be less than  $0.5 \text{ nT}$
- Instrument must be at least 27" from spacecraft
- Maintain cross-section smaller than  $\varnothing 1"$
- Bend angle up to  $112^\circ$

Design areas included the constitution of the composite laminate, hinge window design, and most critically, features to prevent crack propagation. A structurally weaker section of material like this presents unique problems. Many of the design choices were ultimately decided by their effect on hinge robustness during stowage and deployment. Some of the less successful versions are shown in Figure 5. The composite hinge shown in Figure 6 is the result of many design and fabrication iterations.

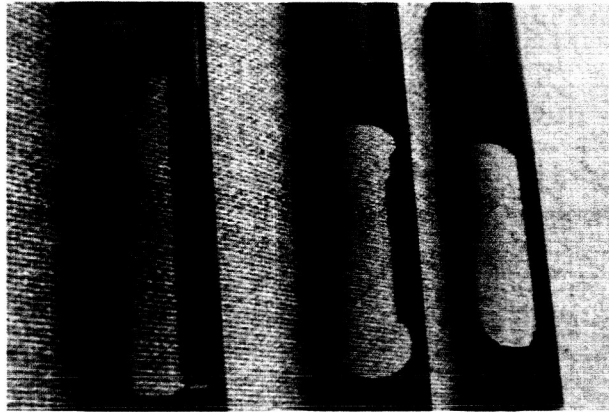


Figure 5 Various Unitary Boom Hinge Window Designs (L to R "Rounded Corner," "Dog Bone," and "Race Track")



**Figure 6 Flexed Unitary Boom Hinge**

#### Laminate

Composite design is always a trade off between desired end-product properties and manufacturability. This is much truer for graphite composites than for other materials such as plastics and metals. What follows is a discussion of some of the design and fabrication challenges inherent in this application.

Parameters that affected the boom laminate were: fiber material, fiber orientation, prepreg type, thickness, and resin type. There was a constant interplay with fabrication issues such as seam closeout, de-bulking of the prepreg and integrity of the finished laminate.

The layup fiber modulus and fiber orientation determined the finished-product properties, so it had top priority. Requirements for maximum thickness, torque margin and deployed stiffness (which governs the natural frequency of the boom on orbit) yielded an acceptable range of graphite material stiffness, depending on fiber modulus and fiber orientation. Uni-directional fibers oriented along the boom axis would give the most efficient use of their structural properties, but keeping the laminate together, especially during machining, proved difficult. Fibers oriented off the boom axis could tolerate higher bend angles since their individual bend radii would be less severe than axial fibers. Additional cross-ply laminates added to the overall thickness, decreased performance and were not that effective in maintaining integrity. Another disadvantage was that orthotropic properties were very hard to maintain since they depend so much on accurate fiber orientation during layup. Uniaxial prepreg with cross plies was highly dependent on accurate layup; it resulted in warping.

A woven fabric ply possessed inherent crack-stops. The disadvantage lay in non-optimum fiber placement for finished stiffness due to the weave. Despite these, it was found that the fabrics presented a satisfactory compromise between stiffness and hinge robustness. Fabrics resulted in much more stable finished product post-machining.

The thickness of the graphite laminate was bounded by minimum stiffness requirements on the low side, and outer fiber strain on the high side. A higher modulus fiber such as M55J would require a thinner ply due to its brittleness. This was compensated for somewhat by its modulus. It turned out that the tradeoff was not even. The brittleness and low strain-to-failure of the high modulus fibers overcame their stiffness properties; their crack susceptibility was disproportionate to their stiffness.

The matrix material became an important issue because the hinge placed high demands on it during stowage and deployment, as well as while stowed and passing through launch environments. When not in the fully deployed configuration, the fibers could not react shear; all this loading had to be carried through the matrix. To maximize shear carrying, a toughened epoxy matrix was selected.

#### Hinge window

The window design started as a rectangular cutout. Issues stemming from the complex strain state of the bent hinge resulted in numerous modifications to the window geometry.

The hinge window height (dimension normal to the boom axis) drove the amount of material remaining for the tape size. A narrow tape (large window height) would result in low torque and deployed stiffness, but easy stowage. A wide tape (smaller window height) would be stiffer, but result in higher internal strain while stowed due to the large cross-sectional arc covered. Optimal window height turned out to be that which resulted in removal of just over half the cross section material.

The window length (dimension parallel to the boom axis) was proportional to the required bend angle. Iterations on this parameter yielded a length of 3 times boom diameter for 45° bend and 3.5 D for 90° bend.

The first window shape change was to round the rectangle's corners since sharp corners were obvious crack starters. Samples of window shapes are shown in Figure 6. The "Dog Bone" geometry had the perceived advantage of higher deployed stiffness since it had more material remaining, and less material at the high strain bend areas.

Unfortunately, experimental and analytical results did not bear out intuition. In practice, the circular ends of the dog bone shape did not relieve enough strain to prevent cracks. The next iteration went to a full radius from one tape to the other. We called this the "Race Track" geometry. The first bending mode deformed shape shown in Figure 4 shows that the hinge flexes like a four bar link with almost all the strain occurring at the tape junction with the full tube section. Thus adding material to the tape center section as in the dog bone configuration did not help deployed stiffness.

### Crack Prevention

Creating a window in the side of an integral graphite composite tube was not a problem from a manufacturing point of view. Fabricating a flexible hinge from that same material proved much more challenging. Once flexed past the buckled point, tight bend radii at the machined edges could easily cause cracks to form and propagate catastrophically through the thin tape section. Several mitigation techniques considered included:

- Stitching a Kevlar<sup>®</sup> fiber as a hem around the machined surface. This had the advantage of direct physical restraint of loose fibers. However it was also manually intensive and the operation would disturb the laminate planarity. Also, the stitch fiber would be almost as thick as the ply it constrained, leaving a very coarse result with poor fiber alignment.
- Increasing resin content significantly. This would reduce fiber volume and liability to crack. It would also decrease stiffness and strength.
- Making the matrix a toughened epoxy. This turned out to be beneficial. As mentioned above, the matrix had to support a much higher fraction of the load while the boom was stowed.
- Implementing fabric prepreg. Fabric is inherently crack-resistant due to the woven fibers.
- Using lower modulus but tougher fibers. This was discussed above, and turned out to be advantageous.
- Applying staking compound directly to the machined window edge. Though done by hand, this was an effective way to cement any loose fibers.
- Overall encapsulation of the finished hinge after machining with a compliant ply such as Kevlar<sup>®</sup>. No way to do this effectively was settled on. In any case it would have required secondary machining.

### Fabrication

The booms were laid up on circular steel rod mandrels. In general, the prepreg manufacturer's compaction and curing instructions were followed. After cure, the windows were machined out.

Boom layup and cure presented issues such as assuring adequate compaction and minimizing seam effects. Voids in critical strain areas would be crack-initiation sites. The prepreg de-bulk procedure was refined to include both shrink-taping and autoclave cycle. Seams of each ply were staggered so as to be off the hinge tape and 180° from each other in adjacent plies. Mandrel removal was assured by tapering the diameter by ~.001" per 10" of length.

Machining the windows required care to prevent fiber pullout. High speed diamond bits specially designed for composites machining were adopted. A conservatively slow feed rate minimized chatter and resulted in a smooth cut. A temporary salt mandrel which filled the cured tube stabilized the window machining operation.

### Conclusion

Instrument and other deployables for space flight vehicles can benefit greatly by using graphite fiber-based materials. The tube form is efficient structurally and from a fabrication point of view. Creating hinges by simply removing material is an efficient way to achieve structural/mechanical goals. Naturally, caution is advised when working with weakened sections that must perform during both launch and mission operations. Further work will improve on the work accomplished so far:

- The fiber and matrix materials could be investigated more, resulting higher stiffness for the same bend properties.
- Investigate elliptical cross-section. This will reduce strains in the stowed boom and bring up the out-of-plane stiffness by increasing the tape width.
- Analysis was halted before the design process finished; it needs to catch up to the current design state. Duplicating the edge-effects of the complex strain field would better predict the failures seen in practice.
- Prototype testing will pave the way for wider application of this hinge material.

A graphite boom solves a wide range of problems for space deployables. This paper has described developments which enable the use of graphite by addressing issues particular to that material.

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